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Multi-criteria assessment of small scale CHP technologies in buildings

Dalia Streimikiene [a,*], Tomas Baležentis [b]

[a] Lithuanian Energy Institute, Breslaujos 3, Kaunas, LT-44403, Lithuania
[b] Lithuanian Institute of Agrarian Economics, V. Kudirkos Str. 18, Vilnius, Lithuania

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ABSTRACT

Lithuania has a strong dependence on foreign energy, mainly Russian oil and gas. The need for replacement of old capacities and closure of Ignalina NPP is an extremely important driving force for transformation, making conventional and new technologies compete for a role in the future energy supply in Lithuania. Lithuania adopted national energy independence strategy in 2012 where construction of new NPP is being considered as the main way to increase energy independence however for Lithuanian population the prices of district heat is the major problem therefore the alternative measures are necessary seeking to solve the problem of energy independence and high district heat prices.

One possible development path of energy sector is decentralization of the electricity system. Distributed power generation in small, decentralized units could help to reduce emissions, save grid capacity and provide opportunities for renewable energy. It could be a constituent part of a more sustainable energy future. There are several available technologies for implementation of CHP in buildings. These technologies need to be assessed by taking into account economic, environmental and social criteria. Comparative assessment of these technologies in terms of sustainability and to define the most sustainable one. The multi-criteria decision making (MCDM) methods are the celebrated techniques employed for suchlike assessments and can by applied for this task as provides assessment of technologies based on quantitative, qualitative indicators and also allows to tackle with uncertainties when ranges of values for indicators are available. The aim of the paper is to compare the main small scale CHP technologies for buildings and to rank them according the main criteria of sustainability.

Contents

1. Introduction

The electricity system in Europe is currently undergoing a process of transformation. Market deregulation has led to mergers and acquisitions in the electricity sector, but has also forced companies to seek out new business areas. Environmental regulations, like the Kyoto process and the European Emissions Trading Scheme, are exposing the sector to external pressure [1]. New technologies, such as renewable energy technologies, combined heat and power (CHP) are emerging.

Lithuania has a strong dependence on foreign energy, mainly Russian oil and gas. The need for replacement of old capacities and closure of Ignalina NPP is an extremely important driving force for

* Corresponding author. Tel.: +370 37 435705; fax: +370 37 351271.
E-mail addresses: dalia@mail.lei.lt (D. Streimikiene), tomas@laei.lt (T. Baležentis).

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transformation, making conventional and new technologies compete for a role in the future energy supply in Lithuania. Lithuania adopted national energy independence strategy in 2012 where construction of new NPP is being considered as the main way to increase energy independence however for Lithuanian population the prices of district heat is the major problem therefore the alternative measures are necessary seeking to solve the problem of energy independence and high district heat prices. One possible development path of energy sector is decentralization of the electricity system. Distributed power generation in small, decentralized units could help to reduce emissions, save grid capacity and provide opportunities for renewable energy.

The concept “small scale CHP” (combined heat and power) means combined heat and power generation systems with electrical power less than 200 kW. The significant benefit of CHP is its overall efficiency, which can be as much as 85%–90%. One of the most promising targets in the application of CHP lies in energy production for buildings [2]. Micro-CHP is taken to mean technologies which could serve a single dwelling. There is no agreed size limit but 10 kW of electrical power might be appropriate. Mini-CHP is taken to be in the range of a few kilowatts to 100 kW and may serve a group of dwellings or a commercial site. Technologies appropriate to this scale include Stirling engines, reciprocating engines and fuel cells [3]. Micro-CHP has several important advantages with regard to key sustainability criteria [2,4–7]:

There are several competing small CHP in the market therefore it is important to make comparative assessment of these technologies in terms of sustainability and to define the most sustainable one. The multi-criteria decision making (MCDM) methods are the celebrated techniques employed for suchlike assessments [8–12].

The aim of the paper is to compare the main small scale CHP technologies for buildings and to rank them according the main criteria of sustainability. The main tasks of the paper are

- To analyze problems of energy consumption in buildings in Lithuania;
- To analyze EU policies aiming at energy efficiency improvements in buildings;
- To define the main characteristics of small CHP technologies for buildings;
- To present the multi-criteria assessment methodology;
- To apply multi-criteria assessment tools for small CHP technologies ranking;
- To develop conclusions for application of small CHP in Lithuanian buildings.

2. Energy consumption in buildings in Lithuania

About 45% of total final energy consumption is used in Lithuanian housing sector. Whereas more than 60% of the Lithuanian population resides in multi-apartment buildings constructed during 1961–1990, which are not complied with the effective requirements, this sector has great energy saving potential [13]. The main indicators of district heat consumption in buildings in Lithuania, Latvia, Estonia and Finland and are presented in Table 1.

As one can see from Table 1 GDP per capita adjusted at PPP in Finland is almost twice higher comparing with Lithuania however the average district heat price in Finland is lower about 30% this indicates the problem of district heat affordability for Lithuanian population. Another important problem which can be noted from Table 1 is the high energy consumption and CO_2 emissions per m^2 of floor area in Lithuania and other Baltic States comparing with Finland. In addition CHP heat autoproduction is available just in Finland and Estonia. Though there are just 30 district heat utilities in Lithuania comparing with 150 in Finland and 200 in Estonia the estimated employment figures in Lithuania are 2.5 times higher than in Finland. Besides that the installed district heat capacity in Lithuania is twice lower than in Finland. This indicates low efficiency and productivity of district heat sector in Lithuania as well as the clear reason of higher district heat prices.

Fraunhofer ISI [14] study evaluated the economic potential of final energy savings in Lithuania as 759 ktoe in 2020, 38% of this energy could be saved in residential and public buildings. The major part of savings, 221 ktoe could be achieved as fuel savings in buildings, mostly for space heating. The rest 68 ktoe of final energy goes to electricity savings, mainly in public buildings. Given the carbon intensity factor of electricity from the grid is 0.707 tCO_2/MWhel, then 68 ktoe of electricity savings correspond to 559 kt CO_2 reduction. Assuming that the carbon intensity factor of district heating is 0.223 tCO_2/MWhh, the savings in heating will yield 573 kt CO_2 [15].

The main policy document to promote energy efficiency in Lithuania is National Energy Efficiency Programme for 2006–2010 approved by the Government of the Republic of Lithuania in 2007. It sets the following targets: renovation of buildings and updating their energy facilities increasing energy efficiency of energy production and use in all sectors, with special attention to district heating, industrial processes, household and transport sector; usage of renewable, local and secondary energy resources. Modernization of multi-apartment buildings is planned in all energy efficiency related Programs. It is expected to modernize

Table 1
Indicators of district heat supply in Baltic States and Finland.

Indicators		Lithuania	Latvia	Estonia	Finland
Energy supply composition for District Heat generated					
Recycled heat	%	57.50%	55%	38.60%	74.96%
Direct renewables	%	13.85%	14.30%	14%	5.92%
Others	%	28.65%	30.96%	47.40%	19.11%
Total District Heat sales in 2009	TJ	27,900	22,042	24,725	116,690
Share of citizens served by District Heating	%	60%	64%	53%	49%
Trench length of District Heating pipeline system 2009	km	2535	1000	1447	12,210
Average District Heating price	Eur/GJ	17.6	13.89	12.25	12.8
GDP per capita adjusted at PPP	US$	19,000	15,900	20,600	36,700
Number of District Heating utilities		30	40	200	ca. 150
Total installed District Heating capacity	MWth	9621	7308	5586	20,790
Estimated employment figures in District Heating sector		4700	2500	6000	1700
District heated floor space	Mill m^2	35	38	30	256
Total share of CHP of national electricity production	%	12.7%	33.6%	9.2%	35.6%
CHP heat autoproduction	TJ			23,709	144,300
Average energy use of buildings per m^2	kWh/m²	217	250	200	133
CO_2 emissions per floor area	$kgCO_2/m^2$	99	90	100	50

at least 70% of all multi-apartment buildings (24,000 units). It is supposed to reduce relative consumption of thermal energy per unit of the used dwelling area by up to 30%, compared with the year 2004. Savings targets for 2010 are 150 GWh if early actions are excluded, and for 2016–1700 GWh. Program started in 2005 and its completion date is the year 2020. During 2007–2008 period the investments in modernization of multi-flat buildings amounted to 58.8 mill. Lt and 480 buildings were renovated. The total energy savings make 13 GWh. From EU Structural funds (2007–2013) 163.5 mill Lt were foreseen for multi-flat buildings renovation to increase energy use efficiency. Achieved energy savings due to renovation of 500 buildings until 2010 makes about 15.3 GWh. Energy saving target (726 GWh in 2010 excluding early actions) set in Energy Efficiency Action plan for 2010–2016 was not implemented in 2010 (achieved savings make just 50% of the target set for 2010). Just in service sector (which accounts just for 5% of total energy saving potential in 2010) the achieved energy savings in 2010 are higher by 205% comparing with target. In household sector (which accounts for 37% of total energy saving potential in 2010) because of faller of the Program of modernization of multi-flat buildings (renovated 980 buildings instead of 24,000) the achieved energy savings 28 GWh makes just 18.6% of targets set by action plan. The new measures to increase energy efficiency in buildings are necessary in Lithuania taking into account not efficient district heat supply system and very high district heat prices for households. The development of small CHP in buildings can be an option.

2.1. EU policies aiming at energy efficiency improvements in buildings

For Lithuania improving the energy performance of buildings is a key factor in solving problems of high district heat prices and securing the transition to a 'green' resource efficient economy and to achieve the EU Climate & Energy objectives, namely a 20% reduction in the GHG emissions by 2020 and a 20% energy savings by 2020. By reducing the energy consumption of the buildings, a direct reduction of the associated GHG emissions will be obtained and a faster and cheaper implementation of renewable energy sources will be triggered. The 2006 Energy Efficiency Action Plan identified residential and commercial buildings as being the sector with the largest cost effective savings potential by 2020, estimated at around 27% (91 Mtoe) and 30% (63 Mtoe) of energy use, respectively. In addition, the Action Plan indicates that, in residential buildings, retrofitting walls and roofs insulation offer the greatest saving opportunities, while in commercial buildings, improving energy management systems is more important. The Eco-design of the Energy-Related Products Framework Directive 09/125/EC, the End-use Energy Efficiency and Energy Services Directive 32/2006/EC, the Energy Performance of Buildings Directive 2010/31/EU as well as the Labelling Framework Directive 2010/30/EU aim to contribute significantly to realising the energy saving potential of the European Union's buildings sector. These main legislative instrument in Europe are aimed to increase energy efficiency in buildings Environmental regulations, like the Kyoto process and the European Emissions Trading Scheme, are also exposing the heating sector to external pressure. One possible development path is decentralization of the electricity system. Distributed power generation in small, decentralized units could help to reduce emissions, save grid capacity and provide opportunities for renewable energy. It could be a constituent part of a more sustainable energy future. Broad implementation of distributed generation, however, would imply thorough structural change and require a surge in innovation. New technologies, such as renewable energy technologies, combined heat and power (CHP) or "clean coal" technologies are emerging and can be used to comply with EU targets provided in Energy and Climate package. But there are still questions that should be asked to identify opportunities improving feasibility for small District Heat (DH) networks and CHP units [16]. Are there industrial, commercial or public buildings with a considerable heat demand, which can facilitate the implementation of small scale DH and CHP? What are the best technologies for installation of small CHP? This is important information for industries manufacturing equipment for DH and CHP. Therefore implementation of EU policies targeting energy efficiency improvements requires additional information for decision makers. Informed decision making allows to define new policies aiming at promotion of the best technologies for small CHP in buildings. The best technologies means the most sustainable one as the sustainability criteria is the main criteria for ranking energy technologies [17].

2.2. Small scale CHP technologies for buildings

Micro CHP (combined heat and power production) is the simultaneous production of heat and power in a single building based on small energy conversion nits. The heat produced is used for space and water heating and possibly for cooling, the electricity is used within the building or fed into the grid. Micro CHP is one of several options for microgeneration, the generation of electricity in individual homes, which is regarded as a potentially disruptive innovation in the energy sector. There are several small scale CHP competing on the market: reciprocating engines, micro-turbines (electric power under 250 kW), Stirling engines, and fuel cells.

In general, the technical features of small scale CHP technologies are well-documented [2,18]. Because of the novelty of the technology in this field of application, however, operational experiences for extended periods have not been available so far. On the other hand, competitive factors have been unwilling to publish the results of their studies. Thus, many uncertainties are still associated with information concerning small scale CHP technologies. In this section, a brief review is presented concerning different CHP technologies.

Reciprocating engine is popular small scale CHP. A power plant based on a reciprocating engine simply consists of a reciprocating engine (diesel, gas, or multiple fuel) and a generator linked to the engine. Typical of this kind of plant is its quite high electrical efficiency, a large power range and a versatile assortment of fuels. Usually, reciprocating engines use natural gas or diesel oil as fuels, but the use of bio-oils and even regenerative biomass is also under research. Engine-based plants are usually delivered as standard modules, which makes them flexible and attractive for use in quite different applications. The applicability of gas engines is at its best in backup systems, whereas diesel engines are recommended for continuous use. Owing to moving parts, the engines need service regularly. In addition, they are noisy and thus not very attractive alternatives for residential applications. Another drawback is their emissions. CO_2 and SO_2 emissions are strongly dependent on the fuel used. The amounts of NO*x*, CO and incombustible hydrocarbons in exhaust gases also depend on other conditions of combustion, like the temperature and the amount of air. Plants based on reciprocating engines are best applicable to buildings with smooth electricity and heat consumption profiles. The larger the size, the greater the benefits [2,18].

The concept "micro-turbines" usually means gas turbines with electrical power generation from 25 kW to 250 kW. In general, a plant consists of a generator, a compressor, a combustion chamber, and a turbine connected to each by a shaft. Air is conducted to the combustion chamber via a compressor and usually a recuperator, in which the heat of exhaust gases is recovered. Because of the high frequency of the alternating current produced by the generator, a rectifier and a transformer are also needed to produce

electricity suitable for electrical devices. Typical of micro-turbine plants are quite low noise and vibration due to their low weight and high rotation speed. Because of their small size, the space requirement is also of minor concern. The high exhaust gas outlet temperature range makes them attractive for heat recovery and production. A drawback is low electrical efficiency, especially on part load. The price of the technology and service costs are also high. From the point of view of emissions, micro-turbines are a little bit more environmentally friendly than, for example, reciprocating engines. Especially, their NO*x* emissions are lower. Natural gas and various liquid fuels (diesel oil, gasoline, methanol, ethanol, etc.) are suitable for micro-turbines. Gas turbines are best applicable to processes with a need for high temperatures (e.g. steam production). In contrast, their applicability for residential purposes is poor because they are expensive and inflexible to load changes [2,18].

The Stirling engine is a reciprocating engine. Contrary to conventional diesel and gas engines, however, its cylinder is closed and combustion takes place outside of the cylinder. The piston moves in the cylinder because of compression or expansion of the working gas (helium, hydrogen) due to the alternating heating and cooling of the cylinder by means of external combustion. Typical of Stirling engines are their rather low emissions (especially NO*x*) and lower noise production than is the case in conventional reciprocating engines. External combustion also causes a decreased need for servicing despite the fact that the maintenance cycle time period is in the same class as for the other reciprocating engines. Due to its external combustion, various fuels are also suitable. An interesting fuel alternative is biomass. A drawback is the rather low electrical efficiency, about 25%–30% when natural gas is used as a fuel. When solid fuels (e.g. biomass) are used, the efficiency can be as low as 15%. The total efficiency, however, is not significantly lower than that of other CHP applications. Stirling engines are very applicable to residential buildings, especially because the electricity/heat ratio is suitable. Their low efficiency, however, supports their use as backup power supplies rather than one in continuous use [2,18].

A fuel cell produces electricity electrochemically, by combining hydrogen and atmospheric oxygen. At its simplest, the fuel cell consists of an anode, a cathode, and an electrolyte. Fuel cells are usually classified into different types according to electrolyte, operational temperature and source of hydrogen. If the fuel is not available as pure hydrogen, it can be released from various fuels by means of a reformation process. There are many factors that make fuel cells beneficial. The most frequently mentioned benefit is its electrical efficiency, which can be up to 45%–55%. Reformation of fuel decreases the efficiency, but an efficiency of approximately 40% is still achieved. On the other hand, the higher the temperature, the better the efficiency. In addition, the electrical efficiency of fuel cells is both quite immune to load changes and not power range dependent. Another benefit is its very low emission rate. If pure hydrogen is used, the only emission is water. If reformation is used, CO_2 and a minimal amount of oxides of sulfur and nitrogen is formed, depending on the fuel. Other benefits are noiselessness, reliability, modularity, and rapid adaptability to load changes. The most important drawback is the investment cost. At the moment, fuel cell plant costs can be even three times higher compared to those of reciprocating engines. Another problem is that fuel cells are more demanding in respect of fuel production, storage, and transportation than other technologies [2,19,20].

The chances for a broad diffusion of innovative micro CHP technologies depend significantly on their economic performance. Reasonable investment costs are a key prerequisite, but other parameters, such as electricity and natural gas prices, technical lifetime, operating costs as well as heat and electricity demand characteristics are also important. However the social characteristics related with use of these technologies in buildings such as power control, size, life time are also very important as they provide information of convenience in use of these technologies by households. Environmental indicators such as emissions also need to be considered by making sustainability assessment of technologies. As economic, social and environmental characteristics seeking to define the most sustainable technology as MCDM is necessary are sometime conflicting.

The main characteristics of small CHP for buildings are presented in Table 2. Based on these economic (electrical efficiency, investment costs, maintenance costs), environmental (loudness, emissions) and social criteria (fuel flexibility, power control, size, life time) which are expressed by quantitative and qualitative indicators these energy technologies will be assessed [2,18]. In addition the problem of uncertainties needs to be dealt because of quantitative indicators presented in ranges of values.

As one see from information provided in Table 2 the most efficient technology is PEM fuel cells however this technology is the most expensive one and having quite low environmental characteristics comparing with cheaper technologies. The one most cheapest technology is Reciprocating engines however this technology has quite low environmental characteristics but quite high social characteristics. Therefore it is obvious that it is impossible to select the most sustainable technology without applying MCDA tools.

2.3. Tackling the uncertainty: interval TOPSIS

Many MCDM involve uncertain estimations, which can be expressed in gray numbers, i.e. their values are considered as intervals [21–23]. The number B is an interval number on the real line $\mathbb{R}$ if it is expressed as $B=[b^l,b^u]=\{b|b^l\le b\le b^u, b\in\mathbb{R}\}$. In case $b^l=b^u$, the interval number is reduced to a real number.

Say we have m alternatives to be rated against n criteria with $i=1,2,...,m$ and $j=1,2,...,n$ being the two respective indices.

Table 2
Criteria for assessment of small CHP technologies.

No.	Criteria	Direction of optimization	Reciprocating engines	Micro-turbines	Stirling engines	PEM fuel cells
1.	Electrical efficiency, full load (%)	Max	25–45	25–30	15–35	40
2.	Electrical efficiency, half-load (%)	Max	23–40	20–25	35	40
3.	Investment costs (US$/electrical kW)	Min	800–1500	900–1500	1300–2000	2500–3500
4.	Maintenance costs (¢/electrical kW)	Min	1.2–2.0	0.5–1.5	1.5–2.5	1.0–3.0
5.	Loudness, scores	Max	1	3	4	5
6.	Fuel flexibility, scores	Max	4	3	4	1
7.	Power control, scores	Max	3	2	2	5
8.	Emission, scores	Max	2	3	4	5
9.	Size, scores	Max	3	4	3	2
10.	Lifetime, scores	Max	4	4	2	2

The criteria can be classified into benefit, $j \in B$, and cost, $j \in C$, ones. The interval rating of the i-th alternative against the j-th criterion is given by $x_{ij} = [x_{ij}^l, x_{ij}^u]$. Then each alternative has the two extreme states: the best situation occurs when an alternative approaches the lower bounds of cost criteria and the upper bounds of the cost criteria simultaneously, whereas the worst situation occurs when an alternative approaches the upper bounds of cost criteria and the lower bounds of the cost criteria simultaneously.

Jahanshahloo et al. [24,25] extended the TOPSIS method [26] by employing interval numbers. Specifically, the interval efficiency TOPSIS [24,25] defines the alternative-variant ideal solutions and thus returns an interval efficiency score for each of the assessed alternatives. The method proceeds as follows:

Step 1. The data are normalized by employing the vector normalization

$$n_{ij}^l = \frac{x_{ij}^l}{\sqrt{\sum_{i=1}^{m}((x_{ij}^l)^2 + (x_{ij}^u)^2)}}, \; n_{ij}^u = \frac{x_{ij}^u}{\sqrt{\sum_{i=1}^{m}((x_{ij}^l)^2 + (x_{ij}^u)^2)}}, \text{ for } \forall i, j \tag{1}$$

where n_{ij}^l and n_{ij}^u are the normalized lower and upper bound of the interval ratings $[x_{ij}^l, x_{ij}^u]$, respectively. One can also construct the weighted normalized decision matrix with its elements $v_{ij} = [w_j n_{ij}^l, w_j n_{ij}^u]$, where w_j is the weight of the j-th criterion such that $\sum_{j=1}^{n} w_j = 1$.

Step 2. Ideal solutions are established for the k-th alternative, $k = 1, 2, \ldots, m$, in the following manner:

(i) The upper bound of the positive ideal solution, A_k^{+u}, is defined by setting all the alternatives in their best situations

$$A_k^{+u} = \{v_1^{+u}, v_2^{+u}, \cdots, v_n^{+u}\} = \{(\max_i v_{ij}^u | i \in B), (\min_i v_{ij}^l | i \in C)\} \tag{2}$$

(ii) The lower bound of the positive ideal solution, A_k^{+l}, is found by setting the k-th alternative to its worst situation and keeping the remaining alternatives at their best situations

$$A_k^{+l} = \{v_1^{+l}, v_2^{+l}, \cdots, v_n^{+l}\} = \{(\max\{\max_{i \neq k}\{v_{ij}^u\}, v_{kj}^l\} | i \in B), (\min\{\min_{i \neq k}\{v_{ij}^l\}, v_{kj}^u\} | i \in C)\} \tag{3}$$

(iii) The upper bound of the negative ideal solution, A_k^{-u}, is found by setting the k-th alternative to its best situation and keeping the remaining alternatives at their worst situations

$$A_k^{-u} = \{v_1^{-u}, v_2^{-u}, \cdots, v_n^{-u}\} = \{(\min\{\min_{i \neq k}\{v_{ij}^l\}, v_{kj}^u\} | i \in B), (\max\{\max_{i \neq k}\{v_{ij}^u\}, v_{kj}^l\} | i \in C)\} \tag{4}$$

(iv) The lower bound of the negative ideal solution, A_k^{-l}, is defined by setting all the alternatives in their worst situations

$$A_k^{-l} = \{v_1^{-l}, v_2^{-l}, \cdots, v_n^{-l}\} = \{(\min_i v_{ij}^l | i \in B), (\max_i v_{ij}^u | i \in C)\} \tag{5}$$

As one can note, both the upper bound of the positive ideal solution and the lower bound of the negative ideal solution are constant for all of alternatives, whereas the lower bound of the positive ideal solution and the upper bound of the negative ideal solution vary across alternatives.

Step 3. The Euclidean distances between each of the alternatives and the ideal solutions for the k-th alternative, $k = 1, 2, \cdots, m$, are measured in the following way:

(i) The distance d_k^{+u} is defined as the distance between the worst situation of the k-th alternative and A_k^{+u}

$$d_k^{+u} = \left(\sum_{j \in B}(v_j^{+u} - v_{kj}^l)^2 + \sum_{j \in C}(v_j^{+u} - v_{kj}^u)^2\right)^{1/2} \tag{6}$$

(ii) The distance d_k^{+l} is defined as the distance between the best situation of the k-th alternative and A_k^{+u}

$$d_k^{+l} = \left(\sum_{j \in B}(v_j^{+l} - v_{kj}^u)^2 + \sum_{j \in C}(v_j^{+l} - v_{kj}^l)^2\right)^{1/2} \tag{7}$$

(iii) The distance d_k^{-u} is defined as the distance between the best situation of the k-th alternative and A_k^{-u}

$$d_k^{-u} = \left(\sum_{j \in B}(v_j^{-u} - v_{kj}^u)^2 + \sum_{j \in C}(v_j^{-u} - v_{kj}^l)^2\right)^{1/2} \tag{8}$$

(iv) The distance d_k^{-l} is defined as the distance between the worst situation of the k-th alternative and A_k^{-l}

$$d_k^{-l} = \left(\sum_{j \in B}(v_j^{-l} - v_{kj}^l)^2 + \sum_{j \in C}(v_j^{-l} - v_{kj}^u)^2\right)^{1/2} \tag{9}$$

Jahanshahloo et al. [24] proved that $d_k^{+l} \le d_k^{+u}$ and $d_k^{-l} \le d_k^{-u}$.

Step 4. The efficiency score of an alternative, R_k, is bounded to the following interval:

$$R_k \in \left[\frac{d_k^{-l}}{d_k^{-u} + d_k^{+u}}, \frac{d_k^{-u}}{d_k^{-l} + d_k^{+l}}\right], \tag{10}$$

The alternatives can be therefore ranked in terms of R_k. Indeed, there have been various approaches suggested for these rankings. In this study we will employ the approach suggested by [27]. They argued that an interval $E = [e^l, e^u]$ can be represented as $W = \langle m(E), w(E) \rangle$, where $m(E)$ and $w(E)$ are, the mid-point and half-width of an interval E respectively. Specifically, $m(E) = 1/2\,(e^l + e^u)$ and $w(E) = 1/2(e^u - e^l)$. Then the acceptability function,

$$A(E \prec D) = \frac{m(D) - m(E)}{w(D) + w(E)}, \tag{11}$$

compares E to A—an another interval number. In case $0 < A(E \prec D) < 1$, E is inferior to A with their bounds overlapped; in case $A(E \prec D) \ge 1$, E is strictly inferior to A.

3. Multi-criteria assessment of small scale CHP technologies for buildings

The criteria and alternatives of the multi-criteria comparison are given in Table 2. This table was transposed before performing MCDM. As one can note the first four criteria are given in interval numbers, whereas the remaining ones are real numbers. The data in table were normalized by employing Eq. (1), see Table 3 for results.

All the criteria were treated as equally important, therefore no weights were used. The positive and negative ideal solutions were found as defined by Eqs. (2)–(5). Thereafter, Eqs. (6)–(9) were employed to estimate the distances between the alternatives and

Table 3
The normalized interval decision matrix.

Alternatives	Criteria									
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Reciprocating engines	[0.266, 0.479]	[0.245, 0.426]	[0.146, 0.273]	[0.233, 0.389]	0.099	0.436	0.327	0.192	0.344	0.447
Micro-turbines	[0.266, 0.319]	[0.213, 0.266]	[0.164, 0.273]	[0.097, 0.292]	0.297	0.327	0.218	0.289	0.459	0.447
Stirling engines	[0.160, 0.373]	[0.373, 0.373]	[0.237, 0.364]	[0.292, 0.486]	0.396	0.436	0.218	0.385	0.344	0.224
PEM fuel cells	[0.426, 0.426]	[0.426, 0.426]	[0.455, 0.638]	[0.194, 0.583]	0.495	0.109	0.546	0.481	0.229	0.224

Table 4
The final ranking of the small CHP.

Alternatives	R_k^l	R_k^u	Mid-point	Half-width	Rank
Reciprocating engines	0.413	0.711	0.562	0.149	2
Micro-turbines	0.480	0.714	0.597	0.117	1
Stirling engines	0.455	0.663	0.559	0.104	3
PEM fuel cells	0.522	0.595	0.558	0.037	4

ideal solutions. The composite efficiency measures were obtained by the virtue of Eq. (10). Moreover, the mid-point and half-width were estimated for each of alternatives (Table 4).

The acceptability functions (cf. Eq. (11)) generally support the ranking provided in Table 4. One can note, however, that the micro-turbines dominate the remaining alternatives to a higher extent than micro-turbines etc. The lowest difference in terms of the efficiency intervals was observed between stirling engines and PEM fuel cells, which can be considered as the two least preferable options.

3.1. *Policy implications*

Up to now deployment of small generators was going comparatively slowly in Lithuania due to domination of Ignalina NPP in the electricity market, surplus of capacities in the power system, lengthy and complicated administrative procedures for investors in small scale electricity generation, lack of transparent standard procedures and requirements for the grid connection, dominant position of distribution system operator in negotiating network access, high fixed constant payment related to control of distributed generation, etc. Due to the existing requirements certain procedures related with the preparation and implementation of power plant projects for the most part do not depend on the capacity of the power plant. Also technical conditions for connecting to the network are relatively strict and require large investments from the new electricity producers. Thus, new small generators hardly can enter the electricity and heat market. One of the most promising distributed generation technologies in Lithuania and other Baltic States is development of small combined heat and power plants and micro-cogeneration. But in a case of cogeneration plants the essential barrier is related to procurement of an additional electricity and heat to networks. The current legislation is more favorable for district heating companies, which due to existing overcapacities in the heat supply infrastructure have no motivation to allow the competitors to enter the market. Small generators have to meet certain technical specifications, which are defined by the network operator. In principle technical standards for connection of distributed generators should be applied, however, in Lithuania technical specifications are not known in advance. As practice shows, technical conditions are relatively strict and require large investments from the new electricity producers. Barriers are related also with authorization, validation of the connection and performance requirements. These barriers arise due to absence of uniform certification and testing procedures for connection of distributed generators to the grid as well as due to lack of technologies and systems for control of large number of small producers.

To promote this technology it is necessary: (1) to ensure that the procedures and rules are objective and transparent taking into consideration specific features of cogeneration technologies, and (2) to facilitate access to the grid for electricity produced by high efficiency cogeneration from small scale producers.

As the most sustainable small CHP technologies are micro-turbines and the stirling engines and PEM fuel cells can be considered as the two least preferable options the policies aiming to promote these small CHP technologies are necessary. First of all it is necessary to improve the policy and regulatory environment for micro-turbines. The funding opportunities should be offered by various entities throughout the country. These opportunities take a variety of forms, including financial incentives, such as grants, tax incentives, low-interest loans and feed-in tariffs, as well as favorable regulatory treatment that removes unintended barriers to micro-turbines such as standard interconnection requirements, net metering, and output-based regulations. Recognizing the numerous benefits CHP provides, policy opportunities include: developing standardized interconnection rules; developing incentive programs for micro-turbines using public benefit funds etc.

4. Conclusions

(1) The high burden of district heat prices for Lithuanian households can be observed. Though GDP per capita adjusted at PPP in Lithuania is almost twice lower comparing with Finland the average district heat price in Finland is lower about 30%. Though there are just 30 district heat utilities in Lithuania comparing with 150 in Finland and 200 in Estonia the estimated employment figures in Lithuania are 2.5 times higher than in Finland. Besides that the installed district heat capacity in Lithuania is twice lower than in Finland. This indicates low efficiency and productivity of district heat sector in Lithuania as well as the clear reason of higher district heat prices.

(2) Lithuanian has twice higher energy consumption and CO_2 emissions per m^2 of floor area comparing with Finland and other old EU member states. This indicates low insulation of buildings and low energy efficiency of heat consumption in buildings having even bigger impact on high burden of district heat prices for Lithuanian households.

(3) Lithuania faces energy supply security problems after closure of Ignalina NPP and the further development of distributed generation would allow to address this challenge including the problem of not efficient district heat supply system available in Lithuania.

(4) Small CHP in buildings should be considered as important measure to deal with the problems in Lithuanian district heat sector and help to improve energy use efficiency in buildings.

(5) As various CHP technologies are available having different economic, social and environmental characteristics the informed decision support measures such as MCDM are necessary to rank these technologies and to define the most sustainable one.
(6) The interval data and interval TOPSIS method were employed to prioritize the four CHP technologies, viz. reciprocating engines, micro-turbines, stirling engines, and PEM fuel cells. The carried out multi-criteria analysis suggests that micro-turbines it the most efficient CHP technology in terms of economic, social, and ecologic criteria. Reciprocating engines was the second best technology. Indeed, the differences between the two remaining alternatives were not too significant.
(7) The policies aiming to promote micro-turbines are necessary starting from improving the policy and regulatory environment for micro-turbines. The funding opportunities should be offered by various entities throughout the country. These opportunities take a variety of forms, including financial incentives, such as grants, tax incentives, low-interest loans and feed-in tariffs, as well as favorable regulatory treatment that removes unintended barriers to micro-turbines such as standard interconnection requirements, net metering, and output-based regulations.

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